Astronomy

Galaxy found napping in the primordial Universe

Jacqueline Antwi-Danso

Observations have revealed a galaxy that stopped forming stars earlier than expected. This discovery offers clues about when the first galaxies emerged and sheds light on how stars formed when the Universe was in its infancy. **See p.53**

Galaxies are broadly classified into two kinds: those that are actively forming stars and those that have halted or 'quenched' their star formation[1]. Quenched galaxies are typically more massive than their active counterparts, because low-mass galaxies are thought to assemble their stars before merging and later ceasing star formation. This hierarchical picture of galaxy evolution is supported by more than a century's worth of observations, as well as by cutting-edge cosmological simulations. But observations from the James Webb Space Telescope (JWST) have added a wrinkle to the picture. On page 53, Looser *et al.*[2] report the discovery of a quenched galaxy, called JADES-GS-z7-01-QU (Fig. 1), that formed very early in the history of the Universe, but is only as massive as the nearby dwarf galaxy, the Small Magellanic Cloud.

Before the launch of JWST, even massive quenched galaxies were extremely difficult to detect. The previous record holder for the most distant quenched galaxy[3] is more than 200 times more massive than JADES-GS-z7-01-QU. The light detected from this galaxy was emitted when the Universe was 1.5 billion years old — at least twice as old as it was when JADES-GS-z7-01-QU was formed, which was within 700 million years of the Big Bang. In general, the light radiated from quenched galaxies at early cosmic times is hard to detect because these galaxies are intrinsically faint; they lack the hot, luminous, short-lived stars seen in star-forming galaxies. The expansion of the Universe also causes the light they emit at ultraviolet and visible wavelengths to be shifted to infrared wavelengths by the time it reaches Earth, where the atmosphere blocks most infrared light.

Consequently, the recipe for a robust detection of even a single quenched galaxy is an optimized strategy involving long-exposure observations and a dash of serendipity. Fewer than 90 quenched galaxies observed with robust spectroscopy can be dated back to the first quarter of the Universe's history. JWST was built precisely for such a daunting task. With up to 100 times the sensitivity of previous telescopes, JWST can detect these faint sources in a fraction of the time taken by its predecessors. It was also designed to observe infrared radiation, which is difficult to do from the ground.

JADES-GS-z7-01-QU was initially identified as a type of object known as a Lyman-break galaxy[4], using observations from the Hubble Space Telescope. Lyman-break galaxies are star-forming galaxies in the distant Universe whose spectra have a sharp discontinuity, or 'break', at wavelengths shorter than 912 ångströms. This break corresponds to light that is absorbed by hydrogen gas both surrounding the galaxy and along the light's path to Earth. A common feature in the spectra of distant galaxies that have undergone star formation within 100 million years of emitting the light observed from Earth, it allows for a precise determination of their distance from Earth. Owing to the expansion of the Universe, the Lyman break in JADES-GS-z7-01-QU's spectrum is observed at a wavelength of around 10,000 Å.

Thirteen years after the Hubble observations, Looser *et al.* used JWST to reveal another break in JADES-GS-z7-01-QU's spectrum, which was shifted to 30,212 Å owing to the expansion of the Universe. This second feature, called the Balmer break, is most prominent in longer-lived, lower-mass stars with lifetimes of up to one billion years, which means that it can be used to estimate a galaxy's age[5]. The Balmer break provided unambiguous confirmation of JADES-GS-z7-01-QU's distance from Earth, previously determined from the Lyman break. Combined with the absence of bright spectral lines typical of star-forming galaxies, the Balmer break was the 'smoking gun' evidence for a quenched galaxy in the early Universe.

Looser *et al.* undertook a rigorous analysis involving four spectral-modelling methods to derive constraints on the physical properties of JADES-GS-z7-01-QU. Although each method made different assumptions about key ingredients — such as stellar evolution, cosmological parameters and how to model the galaxy's star-formation history — the derived physical properties were consistent with each other and ruled out alternative explanations of the data.

Notably, Looser and colleagues' results suggest that JADES-GS-z7-01-QU formed all of its stars in a single, intense burst, and then rapidly became quenched. This 'burstiness' has been studied extensively using cosmological simulations[6,7] and is regulated by fluctuations in gas flowing into and out of galaxies, as well as by interactions with other galaxies. Bursty star formation is common in low-mass galaxies, and particularly in distant galaxies, because more gas was available for star formation at the early times when these galaxies emerged[8,9].

Simulations have previously shown[10] that

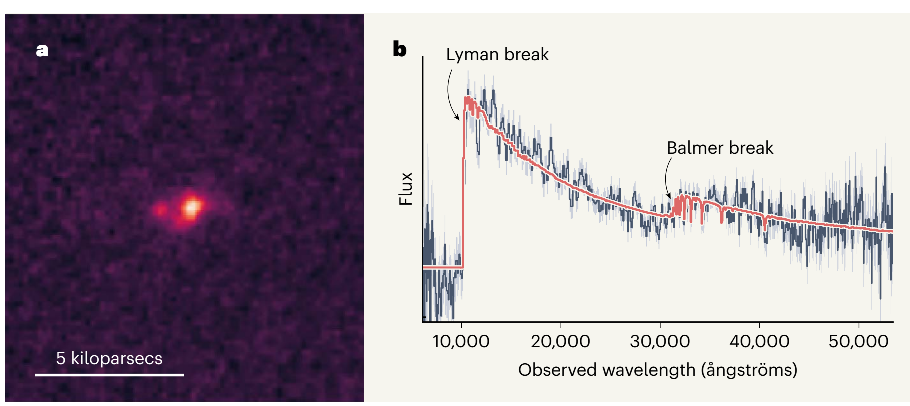

Figure 1 | Image and spectrum of the most distant 'quenched' galaxy. **a**, Looser *et al.*[2] determined that a low-mass galaxy called JADES-GS-z7-01-QU was quenched — that it was no longer forming stars when it emitted the light that the authors observed. **b**, A feature known as the Lyman break had previously been identified[4] in the spectrum of light radiating from JADES-GS-z7-01-QU. This feature allowed the authors to precisely determine the galaxy's distance from Earth. Looser *et al.* used observations from the James Webb Space Telescope (JWST) to reveal a second feature, called the Balmer break, which provides unambiguous evidence that JADES-GS-z7-01-QU is quenched. They then analysed the observed data using four spectral-modelling methods, the fit from one of which is shown here. (Adapted from Fig. 1 in ref. 2.)

galaxies similar to JADES-GS-z7-01-QU go through cycles of intense star formation before quickly becoming quenched. During this process, each successive burst is less disruptive than the previous one, as these galaxies grow their stellar mass and sustain equilibrium between gravity and energetic gas expulsion for longer periods. This means that low-mass galaxies such as JADES-GS-z7-01-QU are quenched only temporarily: they are said to be mini-quenched.

The detection of JADES-GS-z7-01-QU marks the first time that a galaxy has been observed in this mini-quenched phase at such early epochs. Although the exact physical mechanisms responsible for temporary quenching are still unknown, Looser and colleagues' spectral modelling offers some clues. The inferred star-formation history suggests that the event that quenched this galaxy was abrupt. This, in turn, implies a mechanism that ejected gas from the galaxy much faster than it could be replenished.

Supernovae have been shown to do this in low-mass galaxies, but simulations[11] suggest that they are not energetic enough to quench a galaxy with JADES-GS-z7-01-QU's stellar mass. More-powerful mechanisms, such as accreting (growing) supermassive black holes, have been observed in nearby low-mass galaxies[12], but there are no signatures of such objects in the galaxy's spectrum. However, it could be that the radiation from an accreting black hole is heavily obscured by dust, which is common in the earliest galaxies[13].

Looser and colleagues' discovery of JADES-GS-z7-01-QU is undoubtedly exciting, but it leaves us with more questions than answers. Simulations predict that the first mini-quenched galaxies were quenched as early as 600 million years after the Big Bang[10,11,14], which suggests that more will be found now that JWST has given astronomers the technological capabilities to do so. Looser *et al.* have paved the way for statistical studies of this intriguing population. Indeed, since these results were first made public, three more distant mini-quenched galaxies have been discovered[15], including two by members of the same research group as Looser and co-authors[16].

Looking ahead, dozens of candidate galaxies await spectroscopic confirmation with JWST (for example, those studied in refs 8, 9, 16). Growing the pool of mini-quenched samples will be crucial for calibrating models that simulate how galaxies become quenched. The hunt for the earliest quenched galaxies is on.

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Developmental neuroscience

Early origin of vertebrate sympathetic neurons

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The sympathetic nervous system, which enables the fight-or-flight response, was thought to be present only in jawed vertebrates. Analysis of a jawless vertebrate suggests that this system might be a feature of all animals with a spine. **See p.121**

One of the key innovations that arose in vertebrates was the evolution of a branch of the nervous system called the sympathetic nervous system. This forms from cells produced by stem cells that originate in a structure called the neural crest. The sympathetic nervous system is associated with the fight-or-flight response and the neurotransmitter signalling molecules adrenaline and noradrenaline. On page 121, Edens *et al.*[1] report that this system is not found solely in jawed vertebrates, and that the basic building blocks and developmental regulators of a sympathetic nervous system are also present in the jawless vertebrate fish the sea lamprey (*Petromyzon marinus*).

> **"The time course of neuronal differentiation in sea lampreys is surprisingly slow."**

This discovery refines the understanding of the nervous system and how it functions in a vertebrate closely related to the earliest known vertebrates. This landmark study uncovers a characteristic molecular and developmental 'fingerprint' present in noradrenaline-producing (noradrenergic) sympathetic neurons in sea lampreys that is found across many classes of vertebrates, from jawless fishes to mammals (Fig. 1). Studies from the nineteenth and into the twentieth century culminated in the shared opinion that the jawless fishes are not equipped with an 'organized' sympathetic nervous system[2] – represented by structural hallmarks such as a chain of clustered neurons called sympathetic ganglia.

However, the availability of methods to explore gene expression has provided data that revises the old view and establishes the sympathetic nervous system as a pan-vertebrate feature. Edens and colleagues' work completes the search for the evolutionary onset of the principal components of the vertebrate autonomic nervous system – the part of the nervous system (including the sympathetic nervous system) that regulates involuntary processes that are essential for survival. This study marks a milestone in this field of research, the implications of which range from understanding the generation of cell identities across evolutionary time scales to the development of anticancer therapeutics in accessible model organisms.

Edens *et al.* present a detailed picture of the developmental expression of key transcription factors and functional signature genes that are characteristic of sympathetic neurons. The method of *in situ* hybridization chain reaction reveals that transcripts encoding Ascl1, Phox2 and Hand, related to three evolutionarily conserved transcription factor proteins, Ascl1, Phox2b and Hand2 (which are known to be important for sympathetic neuron development in jawed vertebrates) are co-expressed in the same cells in the sea lamprey. These transcription factors were also co-expressed with genes that encode the enzymes tyrosine hydroxylase and dopamine β-hydroxylase, which are involved in the synthesis of noradrenaline.